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Optical and Radio Observations of the Afterglow from GRB 990510: Evidence for a Jet

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ABSTRACT

We present multi-color optical and two-frequency radio observations of the bright SAX event, GRB 990510. Neither the well-sampled optical decay, nor the radio observations are consistent with simple spherical afterglow models. The achromatic steepening in the optical band and the early decay of the radio afterglow, both occuring at $t \sim 1$ day, are evidence for hydrodynamical evolution of the source, and can be most easily interpreted by models where the GRB ejecta are collimated in a jet. Employing a simple jet model to explain the observations, we derive a jet opening angle of $\theta_o = 0.08(n/1\mathrm{cm}^{-3})^{1/8}$, reducing the isotropic gamma-ray energy release of 2.9×10^{53} erg by a factor ~ 300.

Subject headings: gamma rays:bursts – shock waves – radio continuum: general – cosmology: miscellaneous

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1. Introduction

Gamma-ray burst afterglow observations from X-ray through radio can be interpreted in the context of fireball models, where a shock produced by the interaction of relativistic ejecta with the circumburst environment expands into the surrounding medium, producing broadband synchrotron emission (e.g. Mészáros & Rees 1997, Sari, Piran & Narayan 1998, Waxman 1997). The optical lightcurve of GRB 970508, for example, exhibits a monotonic decay; $F_\nu \propto t^{-\alpha}$ with $\alpha = 1.3$ for $\sim$ 200 days (Fruchter *et al.* 1999a), well-described by the expansion of a spherical blast wave (Wijers, Rees & Mészáros 1997). Recently, the rapid decay of some events has been interpreted as evidence for jet-like, or collimated ejecta (Sari, Piran & Halpern 1999), but this explanation is not unique (Chevalier & Li 1999). For GRB 990123, the steepening of the optical lightcurve (Kulkarni *et al.* 1999, Fruchter *et al.* 1999b) combined with the early radio decay (Kulkarni *et al.* 1999) together provide the best evidence to-date for deviations from spherical symmetry. Due to sparse sampling, however, simultaneous steepening in all optical bands – the distinctive feature of hydrodynamic evolution of a jet – was not clearly observed.

The bright *BeppoSAX* event, GRB 990510, is distinguished by excellent sampling of the optical decay in multiple bands, and by the early-time detection and continued monitoring of the radio afterglow. In this Letter we present the optical and radio lightcurves, and argue that in concert they provide clear evidence for evolution that can be understood in the context of relatively simple jet models for the ejecta. The level of collimation implied for this event reduces, by a factor > 100, the energy required to produce the gamma-ray flash.

2. Observations

GRB 990510, imaged by the *BeppoSAX* WFC on May 10.37 (UT) (Dadina *et al.* 1999), was a long ($\sim$75 s) relatively bright event with a fluence (E $>$ 20 keV) of 2.6×10^{-5} erg cm^{-2}, ranking it fourth among the SAX WFC localized sample, and in the top 10% of BATSE bursts (Kippen *et al.* 1999, Amati *et al.* 1999)[11]. After announcement of the WFC position by the SAX team, numerous groups began the search for an optical transient (OT), eventually discovered by Vreeswijk *et al.* (1999a). The OT is coincident with a fading X-ray source seen in the *BeppoSAX* Narrow Field Instruments (NFI) (Kuulkers *et al.* 1999). Spectra taken with the VLT (Vreeswijk *et al.* 1999b) identify numerous absorption lines,

[11] GCN circulars are available at http://lheawww.gsfc.nasa.gov/docs/gamcosray/legr/bacodine/gcn_main.html.

Table 1: B-band Photometry of 990510

Date in May (UT)	Magnitude[a]	Telescope
10.971	19.86 ± 0.05	Yale 1-m
11.058	17.88 ± 0.05	Yale 1-m
11.131	17.95 ± 0.05	Yale 1-m
11.154	18.84 ± 0.06	Yale 1-m
11.180	18.90 ± 0.06	Yale 1-m
11.207	18.98 ± 0.06	Yale 1-m
11.266	19.23 ± 0.06	Yale 1-m
11.292	19.39 ± 0.06	Yale 1-m
11.320	20.11 ± 0.06	Yale 1-m
12.125	20.01 ± 0.08	Yale 1-m
12.171	20.06 ± 0.09	Yale 1-m
12.221	20.89 ± 0.09	Yale 1-m
12.300	21.22 ± 0.12	Yale 1-m
12.996	21.22 ± 0.17	Yale 1-m

determining a minimum redshift of 1.619 ± 0.002. Adopting this as the source redshift implies an isotropic gamma-ray energy release of 2.9×10^{53} erg (we employ a standard Friedmann cosmology with $H_o = 65$ km s^{-1}Mpc^{-1}, $\Omega_o = 0.2, \Lambda = 0$ throughout).

We commenced optical observations of the $3'$ *BeppoSAX* WFC error circle using the Mount Stromlo 50-inch telescope 3.5 hr after the event, and continued using in addition the Yale 1-m on Cerro Tololo, and the 40-inch at Las Campanas. Radio observations began at the Australia Telescope Compact Array (ATCA), in Narrabri, Australia about 17 hours following the GRB. Tables 1, 2, 3 and 4 present the BVRI optical data taken by our collaboration (quoted errors are 1-σ statistical uncertainties). The VR and I lightcurves, along with points from numerous other groups reported in the literature (Galama *et al.* 1999, Kaluzny *et al.* 1999, Stanek *et al.* 1999, Pietrzynski & Udalski 1999a, Pietrzynski & Udalski 1999b, Covino *et al.* 1999, Lazzati, Covino & Ghisellini 1999, Pietrzynski & Udalski 1999c, Marconi *et al.* 1999) are plotted in Figure 1. We have calibrated the reported magnitudes to the Landolt bandpass system (approximately Johnson-Cousins). For calibration, we observed a number of Landolt Stars on May 11 under photometric conditions with the MSO 50-inch. The uncertainty in the zero point of the calibration introduces a magnitude error of ± 0.03 in all bands.

From Figure 1, it is evident that the lightcurve steepens contemporaneously in all

Table 2: V-band Photometry of 990510

Date in May (UT)	Magnitude[a]	Telescope
10.514	17.84 ± 0.02	MSO-50
10.522	17.88 ± 0.02	MSO-50
10.529	17.95 ± 0.01	MSO-50
10.775	18.84 ± 0.06	MSO-50
10.783	18.90 ± 0.08	MSO-50
10.791	18.98 ± 0.05	MSO-50
10.979	19.23 ± 0.04	Yale 1-m
11.011	19.39 ± 0.05	LCO-40
11.508	20.11 ± 0.09	MSO-50
11.512	20.01 ± 0.08	MSO-50
11.516	20.06 ± 0.07	MSO-50
12.146	20.89 ± 0.07	Yale 1-m
12.367	21.22 ± 0.14	LCO-40

bands between day 1 and 2. To characterize the shape, we fit the data with the following analytic four-parameter function:

$$F_\nu(t) = f_*(t/t_*)^{\alpha_1}[1 - \exp(-J)]/J; \quad J(t, t_*, \alpha_1, \alpha_2) = (t/t_*)^{(\alpha_1 - \alpha_2)} \tag{1}$$

The functional form has no physical significance, but provides a good description of the data, and has the property that the asymptotic power law indices are α_1 and α_2 at early and late times respectively. Fitting the V,R, and I data (excluding B due to larger statistical uncertainties) simultaneously yields $t_* = 1.20 \pm 0.08$ days, $\alpha_1 = -0.82 \pm 0.02$, and $\alpha_2 = -2.18 \pm 0.05$, where the errors are formal 1–σ errors, and do not reflect the covariance between parameters. The χ^2 for the fit is acceptable: 65 for 82 d.o.f.. We have, removed 5 out of the 92 total data points with uncertain calibrations. Due to calibration uncertainty, we cannot determine if the lightcurve exhibits variability on timescales shorter than the trend described by the functional fit. The difference in fit parameters from those found by Stanek *et al.* (1999) is due to the slightly different function used. Using the same function, we find consistency with his results to better than 2-σ in all parameters.

To derive the extinction-corrected normalizations, obtained by fitting with the shape described above, we use the astrometric position from Hjorth *et al.* (1999) (RA = 13:38:07.11, Dec = $-80 : 29 : 48.2$ (J2000)) and the dust maps from Schegel *et al.* (1998). The resulting Galactic extinction in the direction of the transient is E(B-V) = 0.20. In the standard Landolt bandpass system, assuming $R_V = A_V/E(B-V) = 3.1$, we obtain $A_B =$

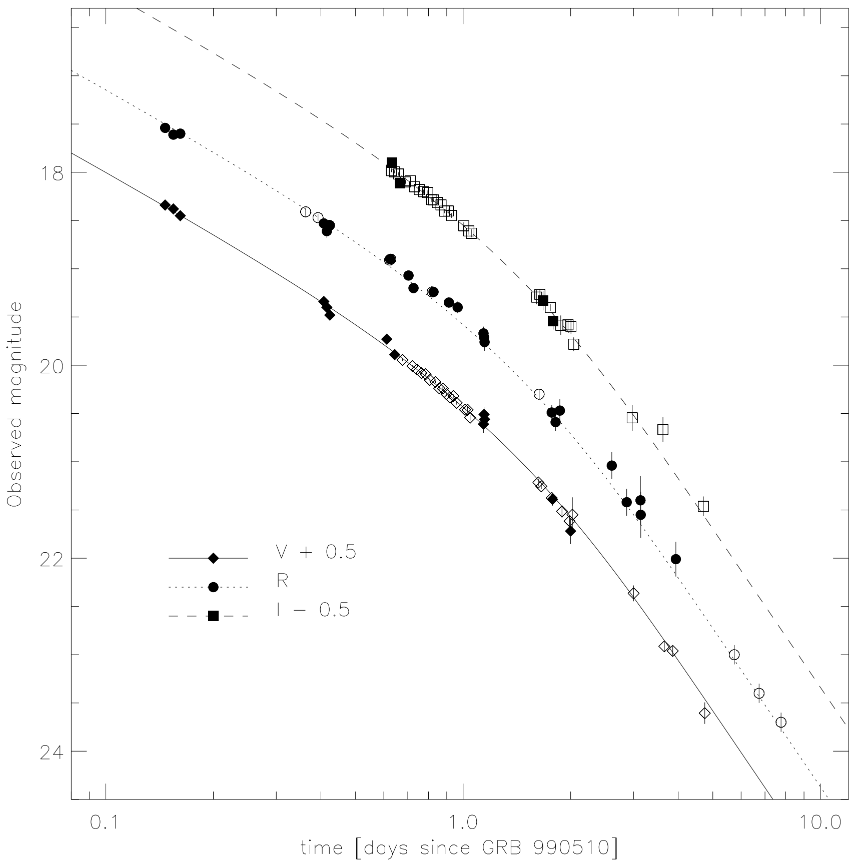

Fig. 1.— Optical light-curves of the transient afterglow of GRB 990510. In addition to photometry from our group (filled symbols – see Table 1), we have augmented the light curves with data from the literature (open symbols). The photometric zero-points in Landolt V-band from our group are consistent with that of the OGLE group (Pietrzynski & Udalski 1999b) and the I-band zero-point is from the OGLE group. Some R-band measurements were based on an incorrect calibration of a secondary star in the field (Galama *et al.* 1999) and we have recalibrated these measurements.

Table 3: R band Photometry of 990510

Date in May (UT)	Magnitude[a]	Telescope
10.514	17.54 ± 0.02	MSO-50
10.522	17.61 ± 0.02	MSO-50
10.529	17.60 ± 0.02	MSO-50
10.775	18.53 ± 0.07	MSO-50
10.783	18.61 ± 0.07	MSO-50
10.791	18.55 ± 0.04	MSO-50
10.992	18.90 ± 0.04	Yale 1-m
11.071	19.07 ± 0.04	Yale 1-m
11.094	19.20 ± 0.04	Yale 1-m
11.194	19.24 ± 0.04	Yale 1-m
11.280	19.35 ± 0.05	Yale 1-m
11.333	19.40 ± 0.06	Yale 1-m
11.508	19.67 ± 0.07	MSO-50
11.512	19.71 ± 0.06	MSO-50
11.516	19.76 ± 0.09	MSO-50
12.138	20.49 ± 0.08	Yale 1-m
12.183	20.59 ± 0.09	Yale 1-m
12.233	20.47 ± 0.12	Yale 1-m
12.975	21.04 ± 0.14	Yale 1-m
13.238	21.42 ± 0.14	Yale 1-m
14.308	22.01 ± 0.18	Yale 1-m

0.87, $A_V = 0.67$, $A_R = 0.54$, $A_I = 0.40$. After correction, the magnitudes corresponding to the flux, f_* in Equation 1 are: $V_* = 19.03 \pm 0.01$, $I_* = 18.42 \pm 0.01$, $R_* = 18.81 \pm 0.01$. The errors are the formal 1–σ errors from the fit, with an additional ± 0.03 mag due to the uncertain zero-point calibration.

Observations of the field around GRB 990510 with ATCA began on 1999 May 10 at 22:36 UT. All observations (Table 2) used a bandwidth of 128 MHz and two orthogonal linear polarizations for each wavelength pair. A radio afterglow is clearly detected, starting $\sim$3 days after the event (Figure 2). The error bars provided in the table are statistical (radiometric) errors only. At early times, variation due to interstellar scintillation will dominate the error in flux determination from the source (see caption Figure 2).

Table 4: I band Photometry of 990510

Date in May (UT)	Magnitude[a]	Telescope
10.999	18.40 ± 0.04	Yale 1-m
12.154	20.04 ± 0.09	Yale 1-m
11.034	18.61 ± 0.05	LCO-40
12.042	19.83 ± 0.10	LCO-40

3. Evidence for a Jet

The majority of other well-studied GRBs, in particular GRB 970228 and GRB 970508, have afterglow lightcurves that decay monotonically for the first month or more, and these have been interpreted in the context of spherical fireball models (e.g. Tavani 1997, Wijers, Rees & Mészáros 1997, Reichart 1997, Granot, Piran & Sari 1999). In the optical, spherical models with typical parameters predict flux rising quickly (within hours) to a maximum value, f_m (at time t_m), after which it decays as a power law, $t^{-\alpha}$ with $\alpha \sim 1$. At later times, the decay becomes somewhat faster (a change in α of 0.25), as the cooling break sweeps across the band (Sari, Piran & Narayan 1998). In the radio band, above the self-absorption frequency, the behavior is similar, but with typical values of $t_m \sim$ 1week.

The observed optical and radio decay of GRB 990510 is quite distinct, showing frequency-independent steepening in the optical and early decline in the radio on a timescale of 1 day; behavior clearly inconsistent with spherical models. An achromatic break or steepening in light curves is expected if the emitting surface has a non-spherical geometry. At any given time, due to relativistic beaming, only a small portion of the emitting surface with opening angle $1/\gamma$ is visible. At early times, (when $\theta_o \gtrsim 1/\gamma$), the observed lightcurve from a collimated source is identical to that of a sphere. As the fireball evolves and γ decreases, the beaming angle will eventually exceed the opening angle of the jet, and we expect to see a deficit in the emission – i.e. a break in the lightcurve. At a comparable or later time (Rhoads 1999, Sari, Piran & Halpern 1999, Panaitescu & Mészáros 1998) the jet will begin to spread laterally, causing a further steepening.

To model the lightcurve, we adopt the afterglow analysis for a jet source given in Sari *et al.* (1999). At early times ($\gamma > \theta_o^{-1}$) the lightcurve is given by the spherical solution; $F(\nu_o) \propto t^{\alpha}$ with $\alpha = -3(p-1)/4$ if the electrons are not cooling, and $\alpha = -3p/4 + 1/2$ if they are. From the GRB 990510 early time optical slope, $\alpha_1 = -0.82$, and we derive $p = 2.1$ assuming the electrons producing the optical emission are in the slow cooling regime, and $p = 1.76$ otherwise. The latter value would result in the electron energy being unbounded, and we conclude that $p = 2.1$. At late times ($\gamma < \theta_o^{-1}$), when the evolution is dominated by the spreading of the jet, the model predicts $\alpha = -p$, independent of the cooling regime. Indeed, our measured value of $\alpha_2 = -2.18 \pm 0.05$ is consistent with this expectation.

The optical data allow us to infer p and the epoch of the break (related to the opening angle of the jet). However, in order to fully characterize the afterglow we also need to determine: (a) ν_a, the self absorption frequency, (b) F_m and t_m and (c) the cooling frequency, ν_c at a given epoch. The optical observations show that even at early times the optical flux is decaying, and is therefore above ν_m. The radio, however, is well below ν_m, and by combining the ATCA and optical data we can derive F_m, t_m, and ν_m. Following Sari et al (1999), we have fitted a $t^{-1/3}$ powerlaw to the four radio points and obtained $F_{8.7\mathrm{GHz}} \cong 204\mu\mathrm{Jy}(t/t_1)^{-1/3}$, where $t_1 = 3.3$d is the time of the second radio detection. Using this and the optical data at t_1 we get $\nu_m(t_1) = 280$ GHz and $F_m(t_1) = 650$ μJy. After the jet begins to spread, ν_m decays as t^{-2}, and we expect ν_m to arrive at radio frequencies at ~ 19 days, producing a break in the radio lightcurve to the t^{-p} slope seen in the optical. In the above, we have assumed that ν_a is below 8.7 GHz. A χ^2 analysis constrains the 4.8 – 8.7 GHz spectral slope to be between -1.3 and 0.4 (95% confidance), consistent with the $\nu^{1/3}$ slope expected if $\nu_a < 8.7$ GHz, and inconsistent with the ν^2 expected if $\nu_a > 8.7$ GHz.

Figure 2 shows the radio lightcurve along with the prediction for both spherical (dotted line) and collimated (solid) ejecta. The relatively sharp transition in the GRB 990510 decay to the asymptotic value $\alpha_2 = -p$ expected when both the jet edge becomes visible and when lateral spreading begins suggest both transitions occur at similar times in this event.

Using the gamma-ray energy of 2.9×10^{53} erg, we find a Lorentz factor at the jet break time of $12(n/1\mathrm{cm}^{-3})^{-1/8}$. This implies an opening angle of $\theta_o = 0.08(n/1\mathrm{cm}^{-3})^{1/8}$, and for a two-sided jet the energy is reduced by a factor $2/\theta_o^2 \cong 300$, to $1 \times 10^{51}(n/1\mathrm{cm}^{-3})^{1/4}$ erg [12].

4. Conclusion

With one of the best-sampled optical lightcurves, and simultaneous early time radio observations, GRB 990510 provides the clearest signature observed to-date for collimation of the ejecta in GRB sources. The achromatic steepening in the optical lightcurve, as well as the early decay, after $t \sim 1$ day, of the radio emission is inconsistent with other observed afterglows that have been modeled with spherically-symmetric ejecta. The GRB 990510

[12]The estimates of Rhoads (1999) will give a smaller opening angle and therefore a lower energy, here we have used the estimates in Sari et al. (1999).

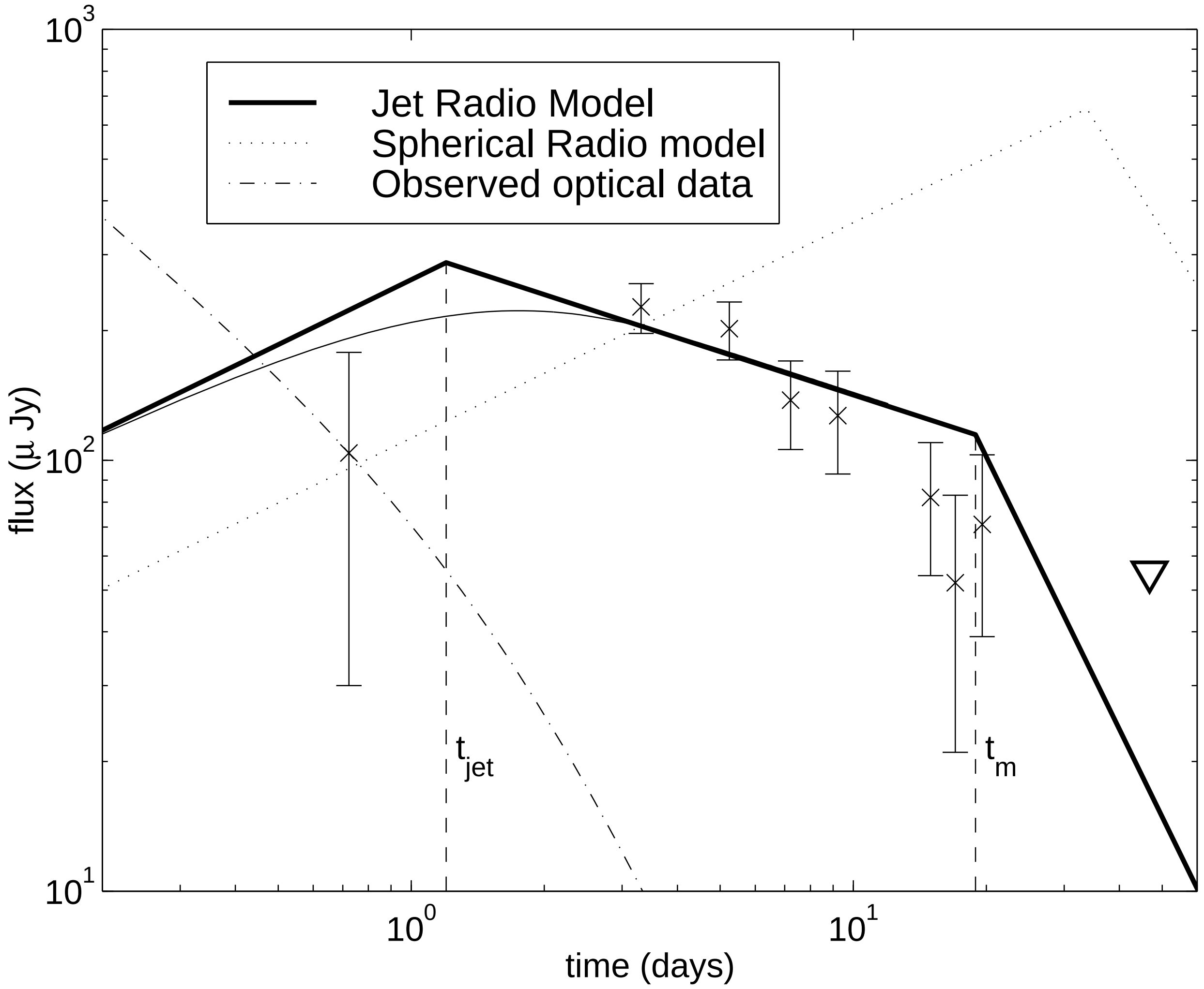

Fig. 2.— Observed and predicted radio lightcurves at 8.6 GHz. Detections are indicated by the crosses, with error bars indicating the rms noise in the image. The true flux uncertainty is dominated by the signal modulation due to refractive interstellar scintillation (e.g. Frail et al. 1997). Using the Galactic scattering model of Taylor & Cordes (1993), and the formalism from Goodman (1997), we calculate a scintillation timescale of 2 hrs in the first few weeks after the burst. Although our typical 8 hour integrations average over the scintillation, we expect modulation of the mean flux density of order 50%. Predictions for the evolution of the radio flux density (solid line) are based on the jet model of Sari et al. (1999) (see text for more details). The dotted line shows the model prediction for a spherical fireball. The dotted-dashed line illustrates the observed optical behavior.

afterglow emission can be remarkably well fit by a simple model for the jet evolution.

It is interesting to ask if the observations to-date are consistent with all GRB engines having an energy release of $\lesssim 10^{52}$ erg, with the wide observed luminosity distribution being due to variation in the degree of collimation. Of GRBs with measured redshifts for which the gamma-ray energy release can be calculated, only GRB 990123 and GRB 990510 show breaks in the optical lightcurves on timescales less than 1 week, and interestingly these are among the highest fluence SAX events to-date. GRB 990123 has an implied isotropic energy release of 3.4×10^{54} erg, which reduces by a factor ~ 100 if the lightcurve break occuring at $t \sim 2$ days is interpreted as the signature of a jet. As argued here, the energy required for GRB 990510 in the context of the jet model is $\sim 10^{51}$ erg. In contrast, 970508 and 970228 show no evidence for a jet in the optical (although 970508 may in radio), however their isotropic energy release is quite modest: only 8×10^{51} erg and 5×10^{51} respectively. The candidates for the largest energy release; highest gamma-ray fluence where no evidence for collimation is seen are GRB 971214 ($z = 3.2$) with $E_\gamma = 3 \times 10^{53}$ erg (Kulkarni *et al.* 1998) and GRB 980703 ($z = 0.966$) $E_\gamma = 1 \times 10^{53}$ erg (Djorgovski *et al.* 1998). Lightcurve observations of these events are, however, limited to $t \lesssim 2$ weeks, and so collimation may still reduce the energy of these bursts by factors of $\sim$40, still consistent with a total energy release $\lesssim 10^{52}$ erg.

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Date in May (UT)	Freq. (GHz)	Flux density (uJy)	Integration (hrs)	Angular Res. (arcsec)
11.09	4.8	110 ± 69	7.5	4.2×1.8
11.09	8.6	104 ± 74	7.5	1.9×1.3
13.68	8.7	227 ± 30	9.0	1.9×1.3
15.61	8.7	202 ± 31	8.0	1.8×1.4
17.58	8.7	138 ± 32	6.6	2.1×1.2
19.59	4.8	177 ± 36	11.4	3.1×2.6
19.59	8.6	127 ± 31	11.4	1.7×1.5
25.32	8.7	82 ± 32	10.6	2.2×1.2
46.81	8.7	-1 ± 28	11.7	4.0×3.6

Table 5: ATCA Radio flux measurements. The date indicates the observation center.